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Gamma Ray Spectroscopy in the Pre-*HESSI* Era

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Abstract. *HESSI* will provide the high-resolution γ-ray spectroscopy not available in early missions. In spite of these spectral limitations the experiments on *SMM*, *Yohkoh*, *GRANAT* and the *Compton Gamma Ray Observatory* have provided data for fundamental discoveries over the past decades relating to particle acceleration, transport and energetics in flares and to the ambient abundance of the corona and chromosphere. These include: 1) enhancement in the concentration of low FIP elements where accelerated particles interact, 2) a new line ratio for deriving the spectra of accelerated particles $\lesssim$ 10 MeV, 3) energies in accelerated ions that exceed those in electrons for some flares, 4) a highly variable ion to electron ratio during flares, 5) concentration of ^{3}He in flare-accelerated particles enhanced by a factor of $\gtrsim$1000 over its photospheric value, 6) an accelerated α/p ratio > 0.1 in several flares and evidence for high ambient ^{4}He in some flares, 7) measurements of the positronium fraction and a temperature-broadened 511 keV line width, 8) new information on the directionality of electrons, protons, and heavy ions and/or on the homogeneity of the interaction region, and 9) the spectrum of broadened γ-ray lines emitted by accelerated heavy ions that indicates Fe enhancements consistent with those observed in solar energetic particles. We discuss some of these and also new developments.

1. Introduction

HESSI promises major advances in our understanding of the origin of high-energy emissions in solar flares. It provides the first capability for high-resolution spectroscopy and arc-second imaging of hard X-rays flares. In order to optimize the scientific return of *HESSI*, it is important to first review the state of our knowledge of high-energy flare emissions. Figure 1 shows the γ-ray spectrum of the 1991 June 4 solar flare observed by the OSSE experiment on *CGRO* (Murphy *et al.* 1997). The captions describe how γ-ray line and continuum studies reveal the physics of flares (e.g. Ramaty, Kozlovsky & Lingenfelter 1979, Ramaty 1986, Ramaty & Murphy 1987; Chupp 1990; Ramaty & Mandzhavidze 1994; Hudson & Ryan 1995; Ramaty & Mandzhavidze 1999).

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14. ABSTRACT
HESSI will provide the high-resolution ?-ray spectroscopy not available in early missions. In spite of these spectral limitations the experiments on SMM, Yohkoh, GRANAT and the Compton Gamma Ray Observatory have provided data for fundamental discoveries over the past decades relating to particle acceleration, transport and energetics in flares and to the ambient abundance of the corona and chromosphere. These include: 1) enhancement in the concentration of low FIP elements where accelerated particles interact, 2) a new line ratio for deriving the spectra of accelerated particles?< 10 MeV, 3) energies in accelerated ions that exceed those in electrons for some flares, 4) a highly variable ion to electron ratio during flares, 5) concentration of 3He in flare-accelerated particles enhanced by a factor of?>1000 over its photospheric value, 6) an accelerated ?/p ratio > 0.1 in several flares and evidence for high ambient 4He in some flares, 7) measurements of the positronium fraction and a temperature-broadened 511 keV line width, 8) new information on the directionality of electrons, protons, and heavy ions and/or on the homogeneity of the interaction region, and 9) the spectrum of broadened ?-ray lines emitted by accelerated heavy ions that indicates Fe enhancements consistent with those observed in solar energetic particles. We discuss some of these and also new developments.

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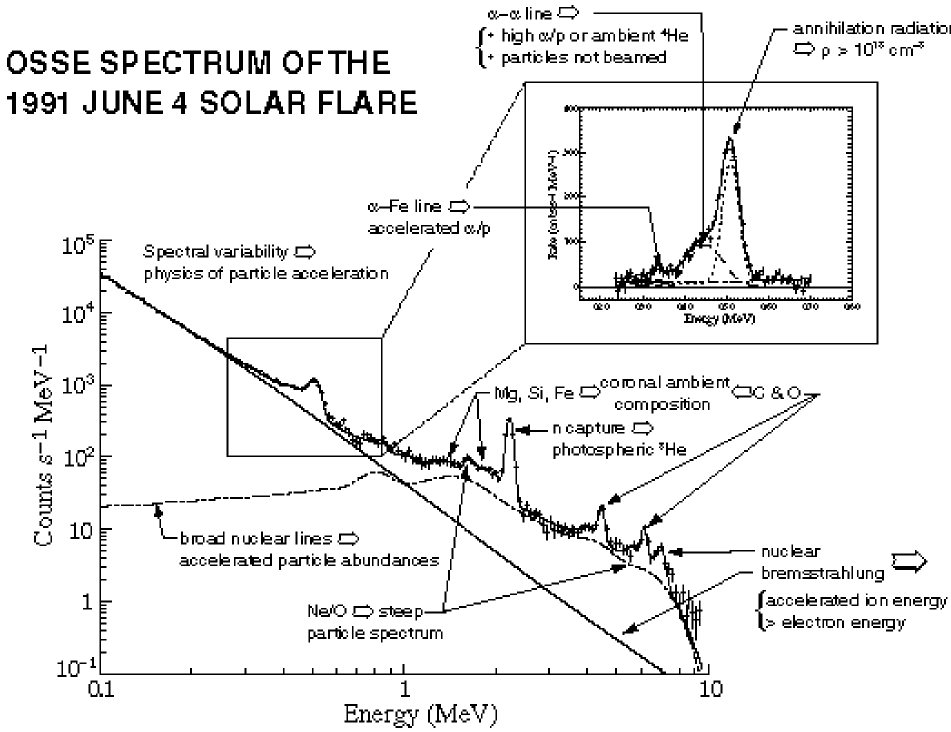

Figure 1. OSSE spectrum of the 1991 June 4 solar flare summarizing the physics to be revealed by gamma-ray spectroscopy.

In this paper we summarize past findings and highlight recent discoveries, some preliminary in nature, based primarily on measurements made by the *SMM*/GRS and *CGRO*/OSSE instruments. A catalog of all the flares observed by the *SMM*/GRS spectrometer has been published (Vestrand *et al.* 1999) and a compilation of high-energy flares observed by the *CGRO*/OSSE instrument is online at http://gamma.nrl.navy.mil/solarflare/flarelib.htm.

2. Electron Bremsstrahlung

The observational picture concerning continuum emissions between 20 and several hundred keV is complicated. This is the key energy domain for understanding the accelerated electron component in flares. A pure power law can fit some spectra, but most spectra show significant deviations from this during some phase of the evolution of the flare at low and/or high energies. Double power-laws with break energies from 30 keV to 100 keV provide adequate fits to the data during the impulsive phase (Lin & Schwartz 1987). The temporal evolution suggests the presence of two components: a spike component (time scale of seconds) exhibiting hard spectra with a break at 30 - 65 keV, and slowly-varying component (time scale of tens of seconds) with a softer spectrum and a break that increases from 25 keV to more than 100 keV through the burst. The

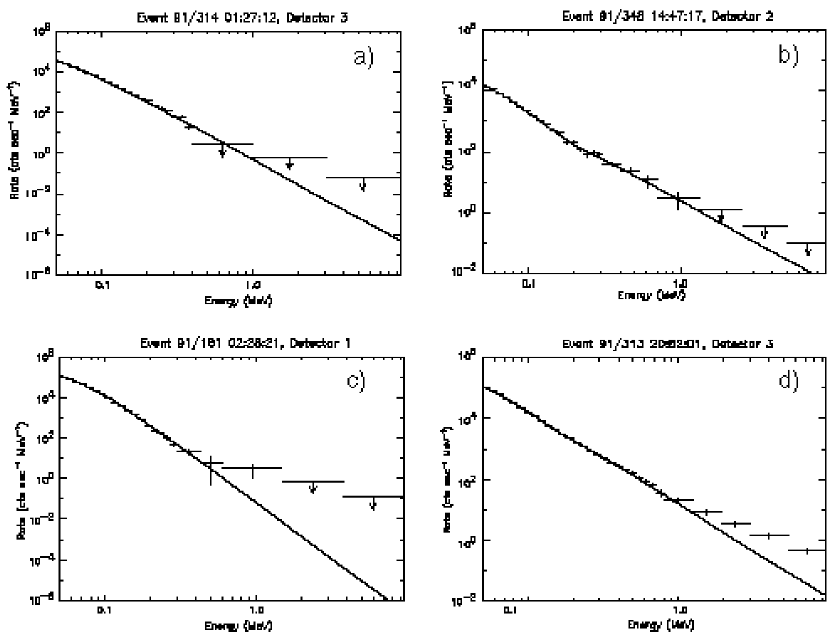

Figure 2. Hard X-ray spectra of four flares observed by OSSE revealing different shapes of electron bremsstrahlung.

breaks in the spectra of the spike component suggest that DC electric fields may play a role and first-order Fermi acceleration (by shocks moving up the ends of the loop) can be the acceleration mechanism for the slowly-varying component.

Continuum spectra also appear to exhibit a hardening at higher energy. Comparison of data from the HXRBS and GRS spectrometers on *SMM* (Dennis 1988) revealed a hardening in the index ($\sim$0.5) of power-law fits $\gtrsim$ 350 keV compared with fits at lower energies; this hardening has been confirmed by the HXS/GRS spectrometers on *Yohkoh* (Yoshimori, *et al.* 1992). There are cases, however, when the hardening is even more noticeable and also cases where no hardening is observed. However, the break occurs near the boundary energy of two spectrometers in both *SMM* (HXRBS and GRS) and *Yohkoh* (HXS and GRS). The *CGRO*/OSSE instrument covers this region with one instrument and has observed four different spectral shapes for the hard continuum. Examples of the four are shown in Figure 2. Plotted are spectra consistent with a single power law, a broken power that softens above about 100 keV, a broken power law that hardens $\gtrsim$200 keV, and one case in which additional hardening is required $\gtrsim$1 MeV.

Directionality of flare accelerated electrons has been inferred by Vestrand *et al.* (1987) based on statistical studies. This appears to conflict with stereoscopic observations that suggest that the hard X-ray emission is isotropic (Kane *et al.* 1998). Li (1995) suggested that the directionality is energy dependent. We have recently performed a study that appears to confirm this supposition. In Figure 3 we plot the heliocentric variation of power law spectral indices for two classes of

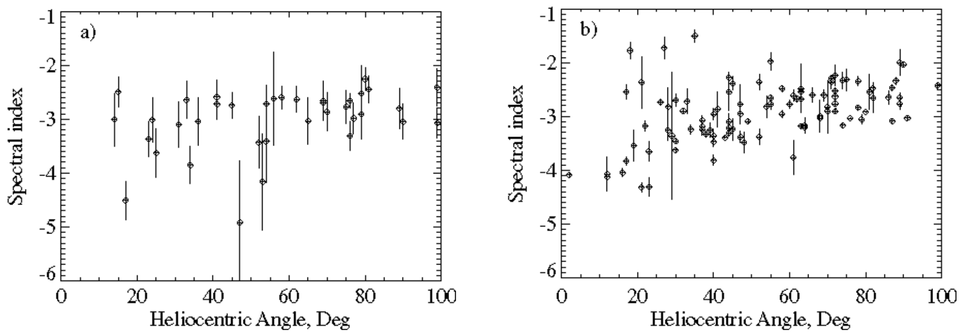

Figure 3. Variation of bremsstrahlung spectral index vs heliocentric angle for a) flares not visible above 1 MeV and b) flares with significant emission above 1 MeV.

flares: a) those detectable primarily below 1 MeV and b) those with significant emission above 1 MeV. We have not analyzed these data in detail but it does appear that, in spite of a large scatter in index, the spectra of harder flares exhibit a softening trend near Sun center that does not appear to be evident in the spectra of the softer flares.

3. Narrow Line Studies

About 30% of all flares with emission >0.3 MeV exhibit characteristic features of ion interactions. Narrow γ-ray line observations are key to understanding the characteristics of accelerated protons and α particles at the Sun. They also provide information on ambient composition, temperature, and density of the flare plasma.

3.1. Hydrogen neutron-capture line

The delayed 2.223 MeV neutron-capture line is the most prominent line observed in spectra of flares that are not too close to the limb. Its narrow width and strength makes it an excellent indicator of the presence of ions in flares. It therefore has been used to search for a threshold in ion acceleration using combined data from *SMM*/GRS and *CGRO*/OSSE (Murphy *et al.* 1993) and for continuous acceleration of ions during solar quiet times (Harris *et al.* 1992, Feffer *et al.* 1997). Measurement of its intensity and temporal variation relative to prompt de-excitation lines has provided information on the spectra of ions above 10 MeV and on the concentration of ^{3}He in the photosphere (Hua & Lingenfelter 1987). The latter measurements are possible because ^{3}He captures neutrons in competition with photospheric hydrogen and therefore affects the decay time of the 2.223 MeV capture line. Observations with *SMM* (Prince *et al.* 1983), *GRANAT*/PHEBUS (Trottet *et al.* 1993), *CGRO*/OSSE (Murphy *et al.* 1997), *CGRO*/EGRET (Dunphy *et al.* 1999a),and *Yohkoh*/GRS (Yoshimori *et al.* 1999a) all suggest photospheric ^{3}He/H ratios of $\sim 2-4\times10^{-5}$. These ratios are dependent on assumptions concerning the depth of interaction and solar atmospheric model, however. We have recently analyzed the summed spectrum

from 19 flares observed by the *SMM*/GRS in search of evidence for 2.223 MeV radiation scattered to lower energies by the photosphere (see Figure 6). We find no evidence for the presence of a strong scattered continuum (Share and Murphy 1999) and set limits that are a factor of 2 to 4 below that calculated by Vestrand (1990); this suggests that the capture line may be produced shallower in the photosphere than believed.

3.2. Positron annihilation

Positrons from decay of radioactive nuclei and from high-energy pions annihilate with electrons to produce the 0.511 MeV line. Comparison of its intensity with the de-excitation lines provides information on both the species of radioactive nuclei and the density of the medium where the positrons annihilate. It is also an excellent diagnostic for flares that exhibit a distinct second stage during which the proton spectrum is hard enough to produce pions (Murphy, Dermer & Ramaty 1987). A classic example is the 1991 July 11 flare observed by the EGRET, COMPTEL, and OSSE instruments on *CGRO* (Kanbach *et al.* 1993, Rank *et al.* 1995, Dunphy *et al.* 1999b). EGRET observed pion emission for several hours after the impulsive phase. The coincident peaking of the annihilation line and high-energy emission observed in the OSSE data (Murphy & Share 2000) suggests that *HESSI* may have the capability of locating the source of this second-stage emission.

Measurements of the 0.511 MeV line width and positronium continuum provide information about the temperature and density of the ambient material. We have made these measurements in eight flares using the moderate resolution spectrometer on *SMM* (Share *et al.* 1996). The positronium continuum/line ratio in the flares are all significantly lower than that measured by *SMM* for the emission from the Galactic plane; this just reflects that the temperatures exceed a few times 10^5 K in the annihilating flare plasma. The width of the annihilation line becomes broad enough to be measured with the GRS at $> 10^6$ K. There is at least one flare (1989 August 16) for which the width has been measured. There is also one flare (1988 December 16) for which a local density of $> 10^{14}$ is required to explain both the line width and low positronium continuum contribution.

3.3. Narrow de-excitation lines

To date 17 distinct and relatively narrow de-excitation lines have been identified in solar flares (e.g. Share & Murphy 1995, 1998). We list these lines and the excited nuclei from which they originate in Table 1. Also listed are the annihilation and n-capture lines. The parameters and their uncertainties were derived using a fit to the sum of 19 flares observed by the *SMM*/GRS. These values are preliminary and will be improved by χ^2 mapping. The energies are somewhat lower but in good agreement with laboratory values; on the other hand the widths are somewhat broader than the 1-2% that is expected (Ramaty *et al.* 1979). This can in part be due to blending of lines unresolved by the NaI detectors. There also is another explanation: line energies are red-shifted for flares that occur near the center of the Sun. This is displayed in Figure 4 where we plot the fitted energy of the C de-excitation line vs cosine of heliocentric angle. This shift of $\sim 1\%$ is also observed in other de-excitation lines but not

in the 2.223 MeV n-capture line. This suggests that the accelerated protons and α-particles are either more strongly directed toward the Sun or that they encounter significantly more material in that direction (i.e. the medium in the interaction region is not homogeneous). It is interesting to note that we found no significant evidence for a red-shift in the α-^{4}He fusion lines (Share and Murphy 1997). This clearly requires more detailed study and will require the excellent spectral resolution of *HESSI* to fully understand the physical implications.

Table 1. Narrow Lines Observed in Solar Flare γ-Ray Spectra

Energy, MeV	Width (% FWHM)	Identification (Energy, MeV)
~ 0.35	$---$	^{59}Ni (0.339)
0.452 ± 0.003	17 ± 2	^{7}Be, ^{7}Li (0.429, 0.478)
0.513 ± 0.002	< 2	e^+- e^- annihilation (0.511)
~ 0.841	$---$	^{56}Fe (0.847)
0.937	$---$	^{18}F (0.937)
1.03 ± 0.01	7 ± 3	^{18}F, ^{58}Co, ^{58}Ni, ^{59}Ni (1.0 0/4/5/8)
1.234	$---$	^{56}Fe (1.238)
1.317	$---$	^{55}Fe (1.317)
1.371 ± 0.005	1.9 ± 2.0	^{24}Mg (1.369)
1.630 ± 0.002	2.8 ± 0.5	^{20}Ne (1.633)
1.781 ± 0.005	3.0 ± 1.4	^{28}Si (1.779)
2.221 ± 0.001	<1.5	n-capture on H (2.223)
2.27	$---$	^{14}N, ^{32}S (2.313, 2.230)
3.332	$---$	^{20}Ne (3.334)
4.429 ± 0.003	3.5 ± 0.3	^{12}C (4.439)
5.300	$---$	^{14}N,^{15}N,^{15}O
6.134 ± 0.005	2.3 ± 0.3	^{16}O (6.130)
6.43	$---$	^{11}C (6.337, 6.476)
6.981 ± 0.012	4.1 ± 0.4	^{14}N, ^{16}O (7.028, 6.919)

Share & Murphy (1995) found flare-to-flare variations in relative line fluxes suggesting that the abundances of elements in the flare plasma are grouped with respect to first ionization potential (FIP). Using the published line fluences and measured cross sections and kinematical calculations, Ramaty *et al.* (1995) showed that the composition of the flare plasma is, on average, close to coronal. However, the flare on 1988 December 16 was depleted in low FIP emission lines which suggests a composition similar to that of the photosphere. As discussed in the section on positron annihilation above, there is other evidence for believing that the γ rays from this flare may have been produced at depths where the composition was closer to photospheric. This suggests that flare particles may interact in regions with compositions ranging from those found in the upper photosphere to those in the corona. Recently reported spectroscopic measurements of flares with OSSE (Murphy *et al.* 1997) and *Yohkoh* (Yoshimori *et al.* 1999b) suggest that the ambient composition may also change within flares. This implies that ions accelerated in different flares and at different times in flares may

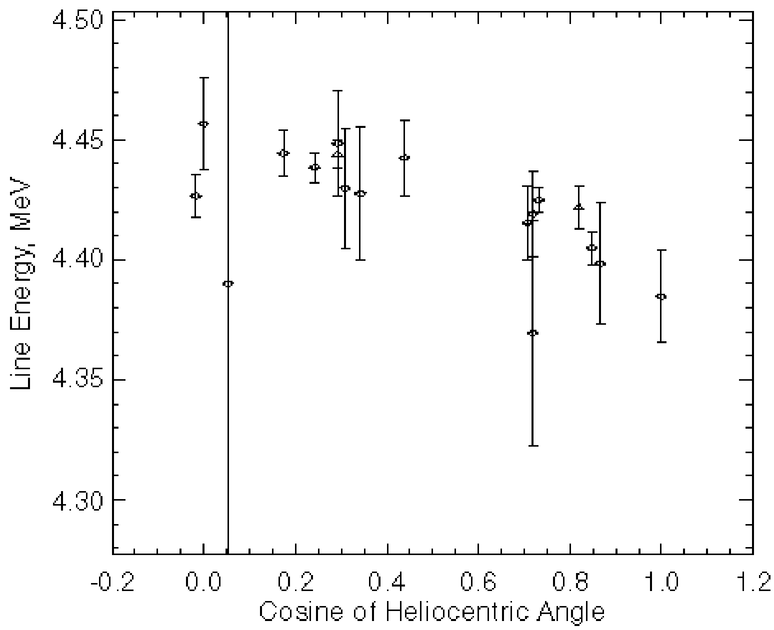

Figure 4. Variation of narrow C line energy with cosine of the heliocentric angle.

interact at significantly different depths in the solar atmosphere. This could happen, for example, if the height of the magnetic field mirroring point varies.

4. Accelerated Helium in Flares

The inset of Figure 1 shows a detail of the region containing α-He fusion lines (see Table 1). We have found high fluxes in these lines relative to the de-excitation lines in the 1991 June 4 flare (Murphy *et al.* 1997) and in the *SMM*/GRS flares (Share and Murphy 1997). This led us to conclude that the accelerated α/p ratio typically had to be large, $\sim$0.5, for an assumed ambient ^{4}He/H abundance ratio of 0.1. Mandzhavidze *et al.* (1997) also suggested that the ambient ratio might be higher in some flares and described a way in which γ-ray spectroscopy could distinguish between the two explanations. This required the measurement of other lines which result from interactions of α-particles on ^{56}Fe. There is evidence for a weak line at 0.339 MeV from such interactions (see inset of Figure 1) in the spectra. Based on this we concluded that, on average, the ambient ^{4}He abundance is consistent with accepted photospheric values and a high accelerated α/p ratio is needed (Share and Murphy 1998). Mandzhavidze *et al.* (1999) performed studies of individual flares and concluded that there is evidence for both a higher accelerated α/p ratio and enhanced ambient ^{4}He.

These same spectral studies have provided information on the accelerated ^{3}He/^{4}He ratio in flares. Shown in Figure 5 is the summed spectrum of 19 *SMM* flares revealing the 0.847 and 1.238 MeV lines from ^{56}Fe, the weak newly-

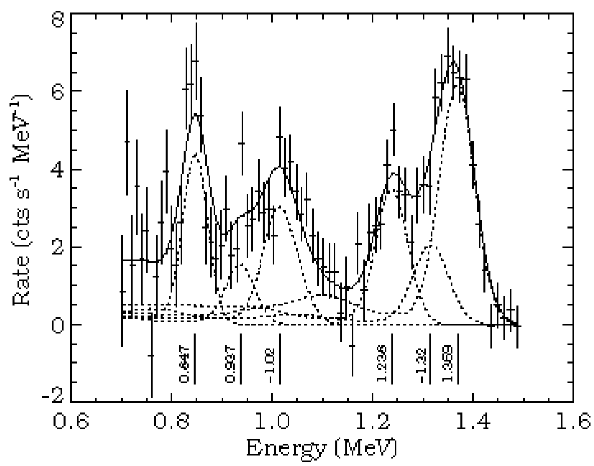

Figure 5. Gamma-ray spectrum revealing lines between 0.7 and 1.5 MeV observed in the sum of 19 *SMM*/GRS flares. The line energies are identified.

observed line from ^{55}Fe at 1.317 MeV, and the strong ^{24}Mg line at 1.369 MeV. For clarity the best-fit bremsstrahlung, highly broadened lines, and instrumentally degraded radiation have been subtracted before plotting. The key line features for understanding the ^{3}He abundance appear near 0.937 MeV and 1.03 MeV. The relative strength of the 1.03 MeV feature suggests a high accelerated α/p ratio from interactions on ^{56}Fe, significant ^{3}He interactions on ^{16}O, or both. There is evidence for ^{3}He in the 4 σ detection of the 0.937 MeV line in the sum of 19 *SMM* flares and in the shift of the data points to higher energies in comparison with a model for ^{3}He/^{4}He = 0. This suggests a flare averaged ^{3}He/^{4}He ratio of $\sim$0.1, $10^{3}\times$ the photospheric ratio. Mandzhavidze *et al.* (1999) performed studies of individual *SMM* flares and concluded that a ^{3}He/^{4}He ratio of 0.1 was consistent with all the flares and that a ratio as high as 1 could occur in some flares.

5. Accelerated Heavy Ions

We have recently demonstrated the ability to spectroscopically reveal the broad γ-ray lines from interactions of accelerated ions with ambient H and ^{4}He in data obtained by *CGRO*/OSSE and *SMM*/GRS (Share and Murphy 1999). Broad lines attributable to accelerated ^{56}Fe and ^{12}C appear reasonably well resolved in the summed 19 flare spectrum (Figure 6) from the *SMM*/GRS after the bremsstrahlung continuum and narrow lines have been removed. The broad lines have widths of $\sim$30% FWHM and appear to be red shifted by $\sim$10%. What is surprising is that large red shifts still persist for flares near the limb. Broad lines from ^{24}Mg, ^{20}Ne, and ^{28}Si can not be resolved from each other. Also complicating the interpretation of data in the 1 to 3 MeV region is the presence of an unknown contribution from unresolved lines. The higher energy ^{16}O lines are blended. Comparisons of broad-line fluxes from accelerated nuclei with the

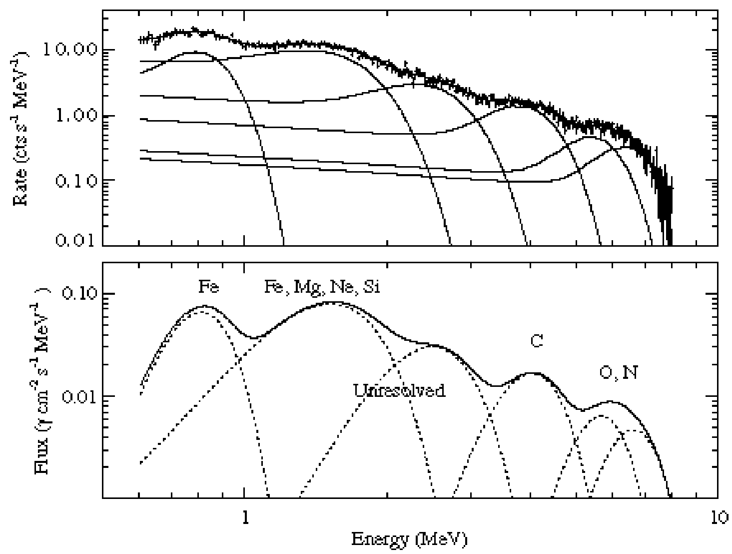

Figure 6. Gamma-ray spectrum revealing broad lines from accelerated heavy ions. a) count spectrum after subtracting narrow lines and bremsstrahlung continuum; b) inferred photon spectrum with lines identified.

respective fluxes in narrow lines from the ambient material measure the relative enhancements in the accelerated particles. We find that the accelerated ^{56}Fe abundance is enhanced over its ambient concentration by about a factor of 5 - 10, consistent with that measured in solar energetic particles in space from impulsive flares (Reames *et al.* 1994).

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